CDF and DØ Heavy Flavor Studies

- Preliminary CDF Run I B Correlation Results
- Preliminary CDF Run II Direct Charm Cross Section
- Preliminary DØ Run II b-jet Cross Section
- Preliminary DØ and CDF Run II J/ψ Cross Section

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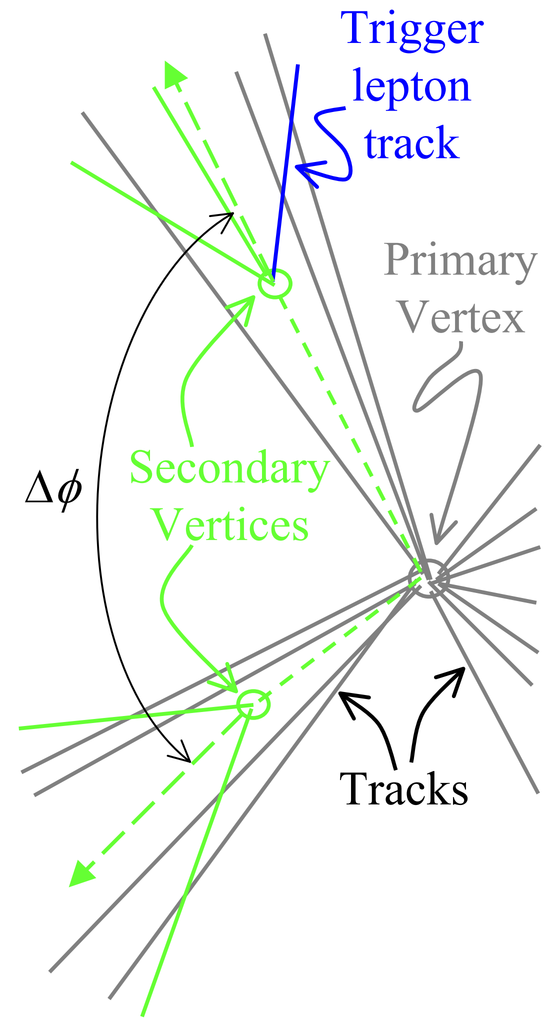
CDF *B* Hadron Correlations (Run I)

- Measurement of $\Delta\phi$ using secondary vertex tags
  - $\Delta\phi$ = "transverse opening angle," angle between B hadrons in plane perpendicular to beams
  - Secondary vertex tags
    - Track-based reconstruction of *B* decay points
    - Allows sensitivity at small opening angles
- Motivation
  - Explore $\Delta\phi$ distribution at small opening angles
    - Previous measurements not sensitive in this region
    - Higher order contributions (gluon splitting and flavor excitation) important at small opening angles
  - Compare measured data to leading-log Monte Carlo predictions (PYTHIA and HERWIG)

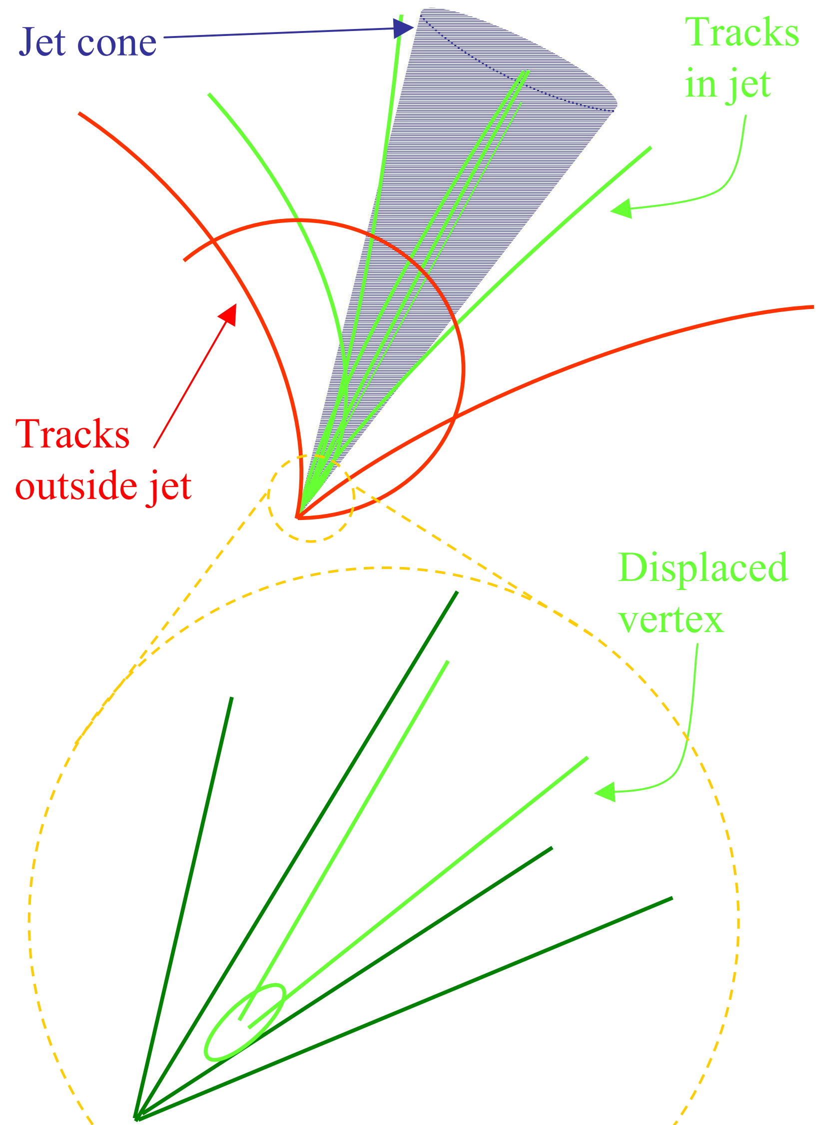
Secondary Vertex Tag Correlations

- Sample enhanced in *B* content
  - 8 GeV electron and muon triggers
  - *B* hadron $p_T \approx 14$ GeV/c
- Reconstruct both *B* decay vertices
  - Trigger lepton within $\Delta R = 1.0$ of one vertex tag
  - Non-trigger *B* hadron $p_T \approx 7.5$ GeV/c
- Use angle between p_T vectors to measure $\Delta\phi$
- Compare to Monte Carlo predictions
- Remove backgrounds and correct for detector effects



Secondary Vertex Tagging

- Locate the event primary vertex to within ~17 μm (on average)
- Organizes tracks into jets using a cone of $\Delta R = \sqrt{\Delta\phi^2+\Delta\eta^2} = 1.0$
- Searches each jet for one or more displaced secondary vertices in two passes
  - Pass 1: require 3+ track vertices
  - Pass 2: 2 track vertices, tighter cuts
- Additional requirements
  - Displaced from primary by at least 2σ
  - Separated from other secondary vertices by at least 2σ

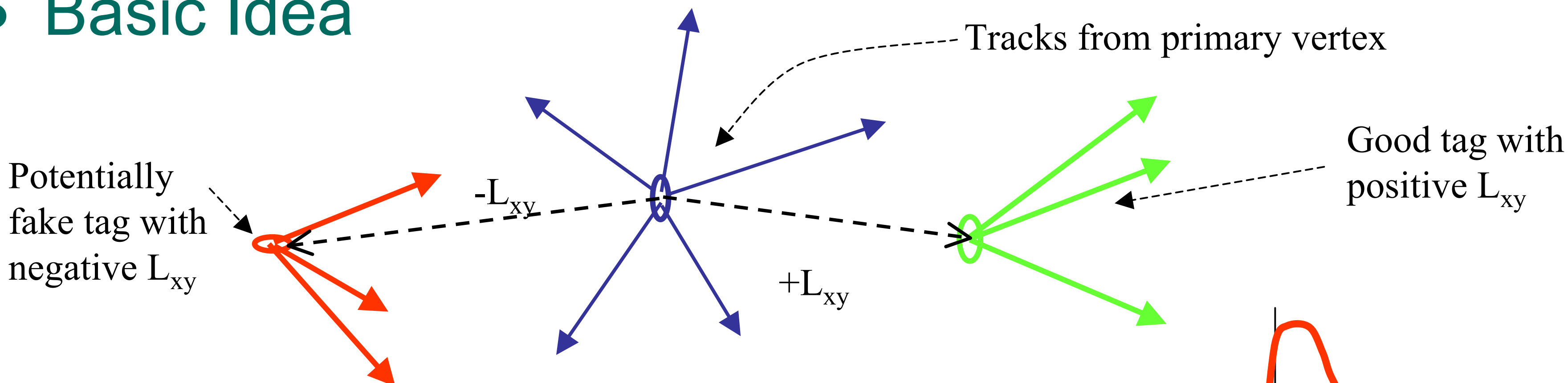


Backgrounds

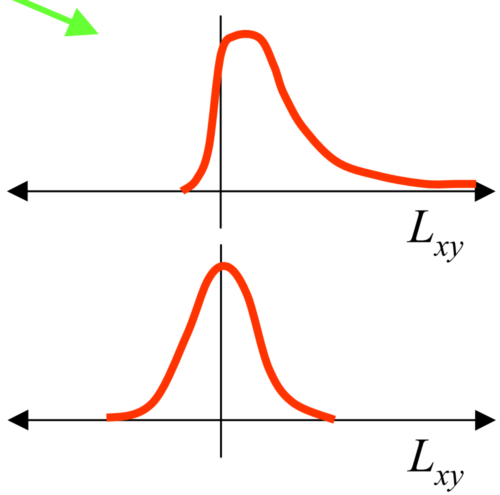
- Mistags
  - Random combination of tracks form a vertex
  - Subtract statistically using L_{xy} (signed 2-D decay distance), similar to side-band subtraction
- Prompt Charm production
  - One or more tags coming from prompt *D* decay
  - $c\bar{c}$ (tag both *D* hadrons) and $b\bar{b} + c\bar{c}$ (tag *B* and *D*)
  - Estimated to be no more than 10% contribution from MC and data
- Sequential Double-Tags
  - Tag same *B* decay twice (often from $B \rightarrow D \rightarrow X$)
  - Mostly eliminated by 6 GeV/c^2 tag pair mass cut
  - Negligible residual contribution estimated from MC
- After mistag subtraction
  - > 90% $b\bar{b}$ purity (most of rest is $c\bar{c}$ and $b\bar{b} + c\bar{c}$)
  - 17,000 double-tagged events in electron and muon samples combined

Mistag Subtraction

- Basic Idea



- L_{xy} is the distance between vertex and primary in x-y plane
- Good Tags: mostly $L_{xy} > 0$
- Mistags: equally likely to have positive or negative L_{xy}
- Use distributions from negative tags to subtract mistag component



Monte Carlo Samples

- PYTHIA 6.2 with different amounts of initial-state radiation
  - PARP(67) = 4.0 (higher ISR, default before version 6.138)
  - PARP(67) = 3.0 (intermediate ISR)
  - PARP(67) = 1.0 (lower ISR, default after version 6.138)
  - Used Rick Field's tuning for underlying event
- HERWIG 6.4 sample, mostly default parameters
- All use CTEQ5L parton distribution functions
- Use default PYTHIA and HERWIG fragmentation models
- Use QQ for *B* decays
- Special care taken to generate all three production mechanisms (over 1.3 billion events generated total)
- Use detector simulation, trigger simulation to make MC look as much like data as possible
- Processed through reconstruction and analysis code, just like data.

Comparisons between MC and Data

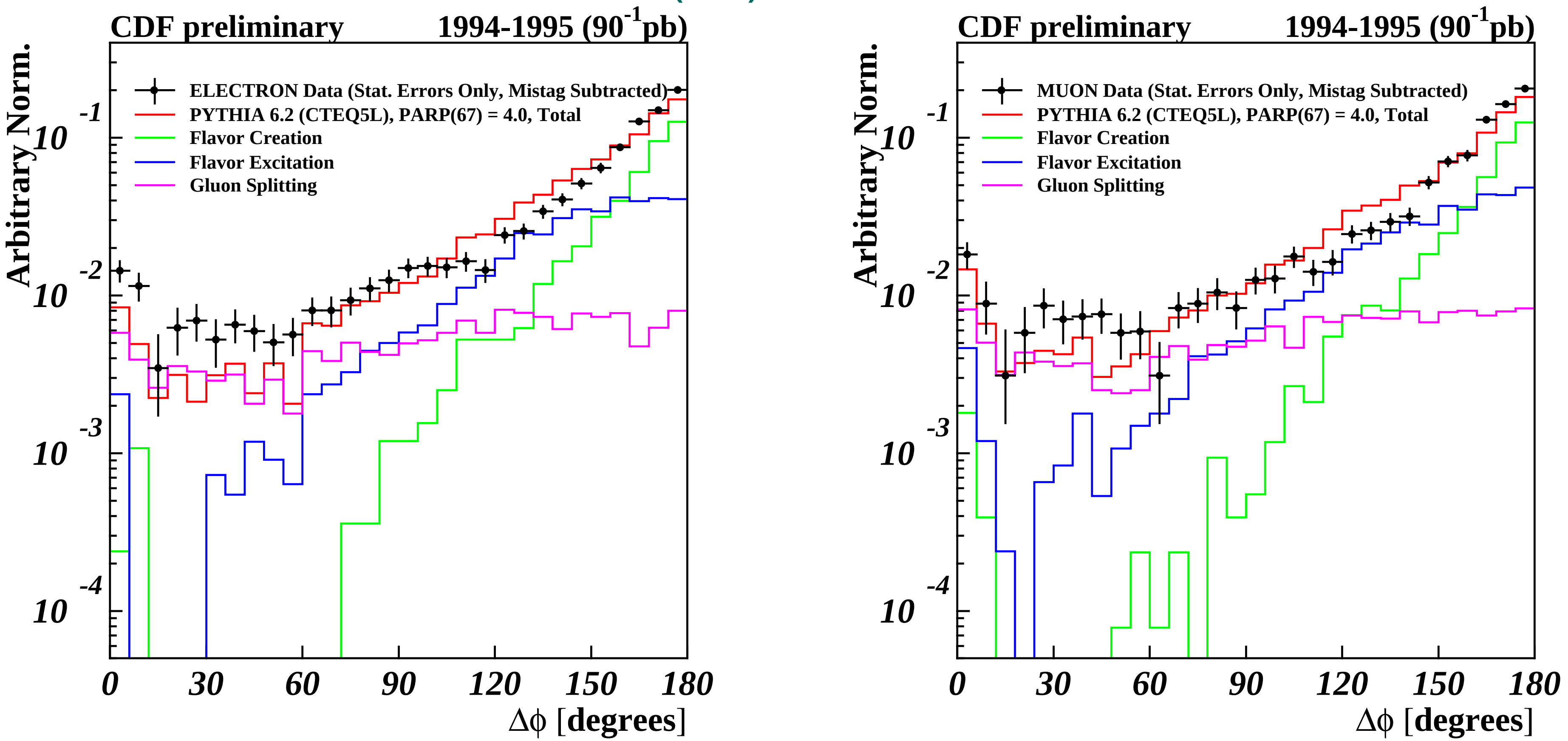
- Monte Carlo and data treated the same way (analysis code, mistag subtraction, etc.)
- Normalization between data and MC:
  - “Fixed” Normalization
    - Relative normalization of three production mechanisms (flavor creation, flavor excitation, and gluon splitting) fixed to MC prediction
    - Overall normalization varied to get best match to data
  - “Floating” Normalization
    - Normalization of each production mechanism varied to get best match to shape in data

Comparisons with PYTHIA, PARP(67) = 4.0 (more ISR)

Normalization fixed to PYTHIA predictions

MC broader than data near $\Delta\phi = 180°$

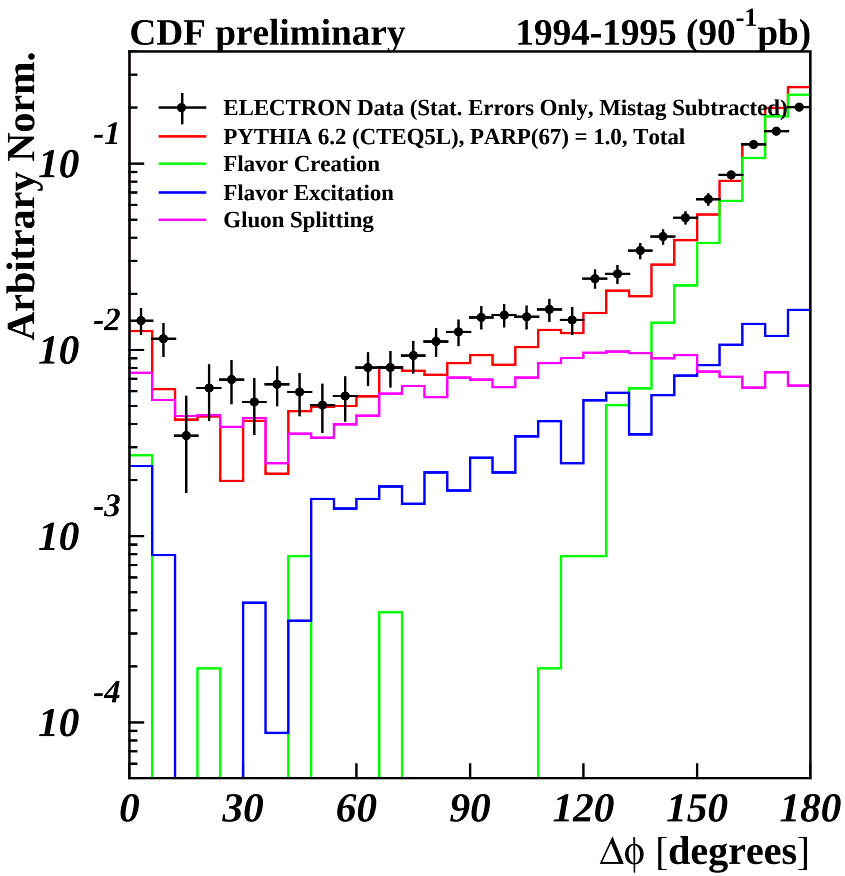
PARP(67) = 3.0 similar

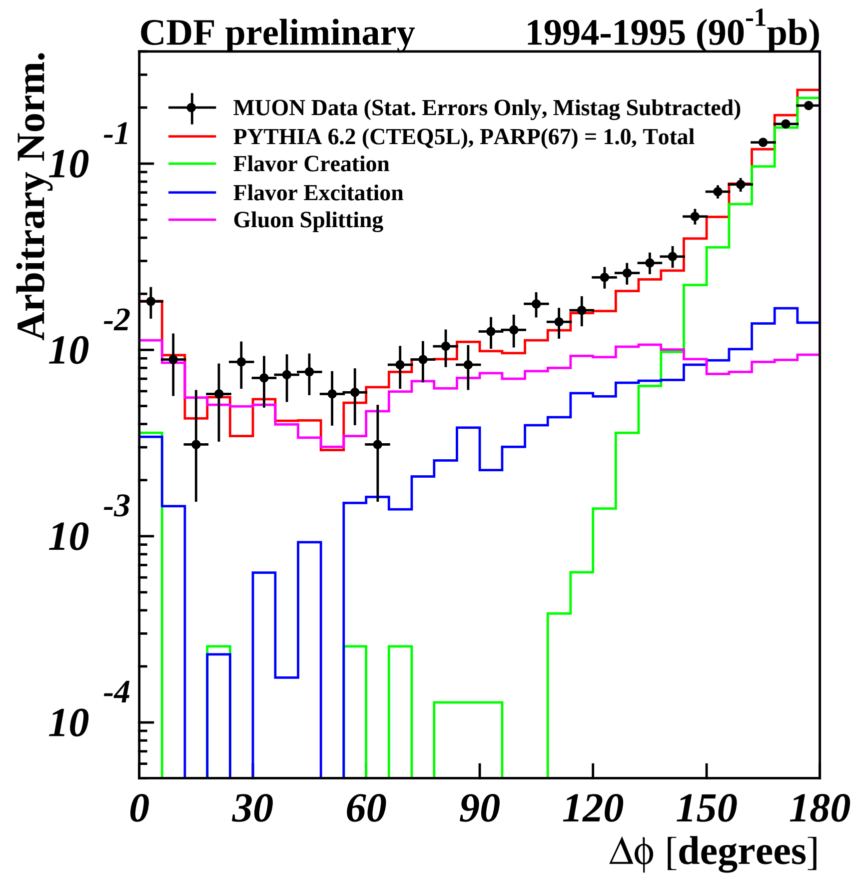


Comparisons with PYTHIA, PARP(67) = 1.0 (less ISR)

Normalization fixed to PYTHIA predictions

MC more narrow than data near $\Delta\phi = 180°$

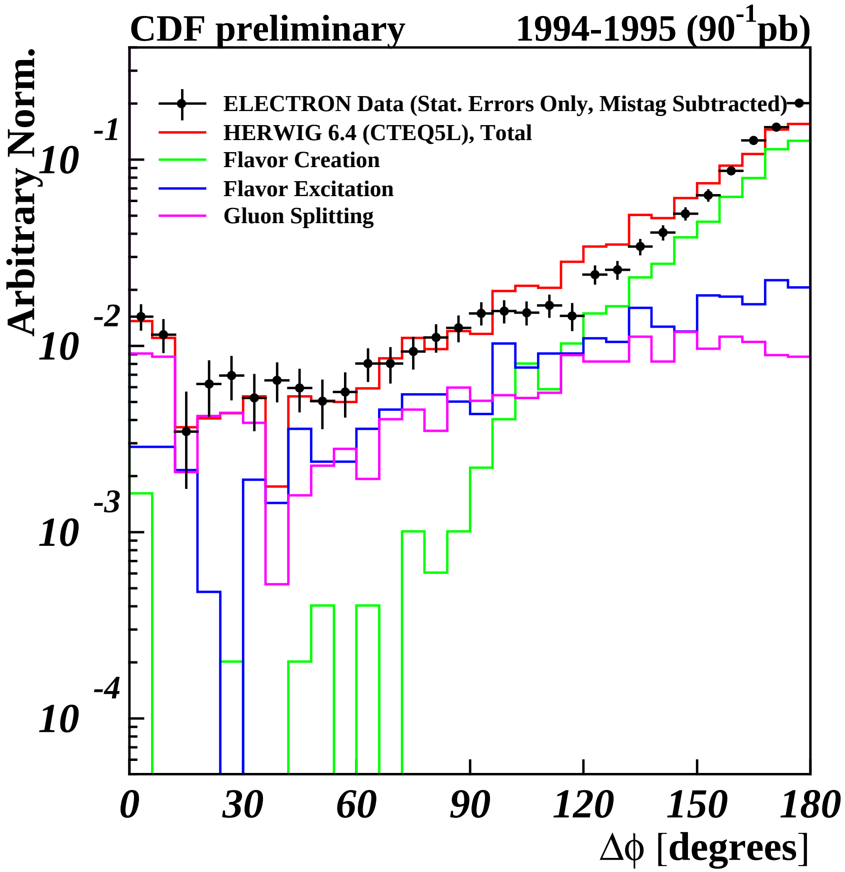


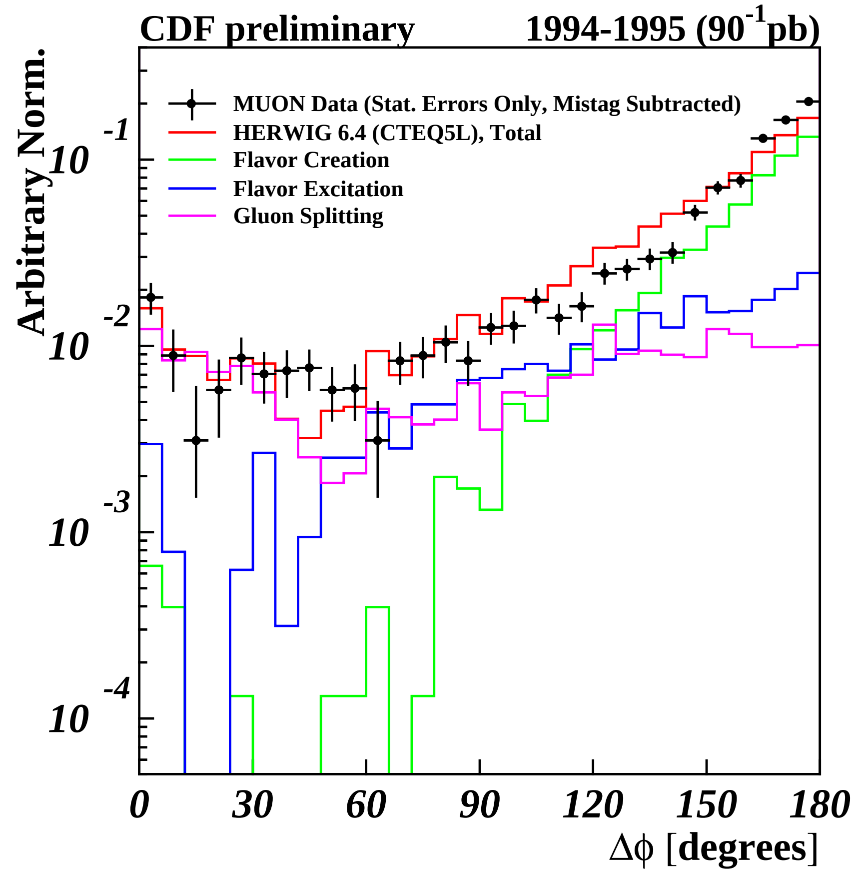


Comparisons with HERWIG

Normalization fixed to HERWIG predictions

MC broader than data near $\Delta\phi = 180°$

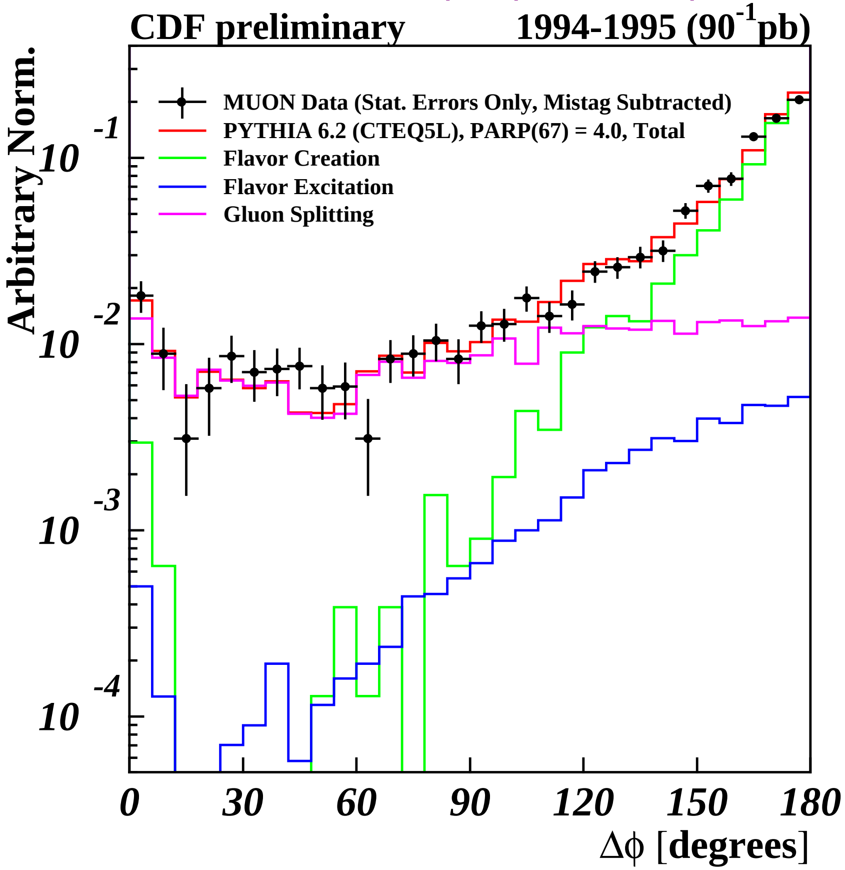




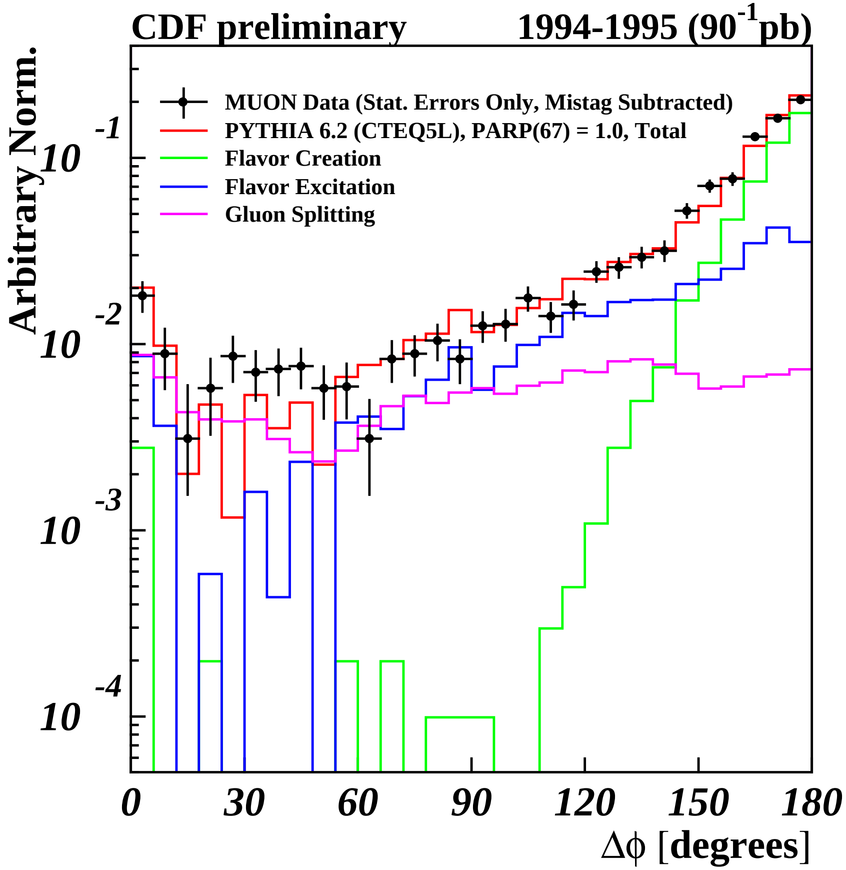
PYTHIA Comparisons with Floating Normalizations

PYTHIA does surprisingly well with PARP(67) = 4.0 or 1.0

- PARP(67) = 4.0 (more ISR) has less flavor excitation
- PARP(67) = 1.0 (less ISR) has more flavor excitation



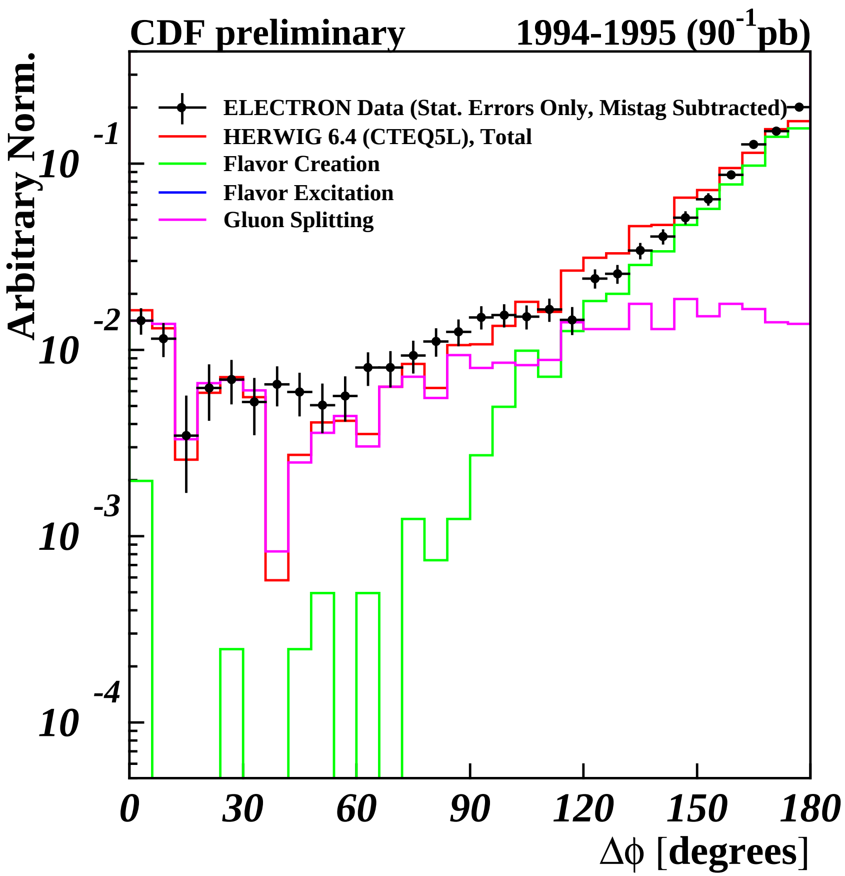
PARP(67) = 4.0 (more ISR)

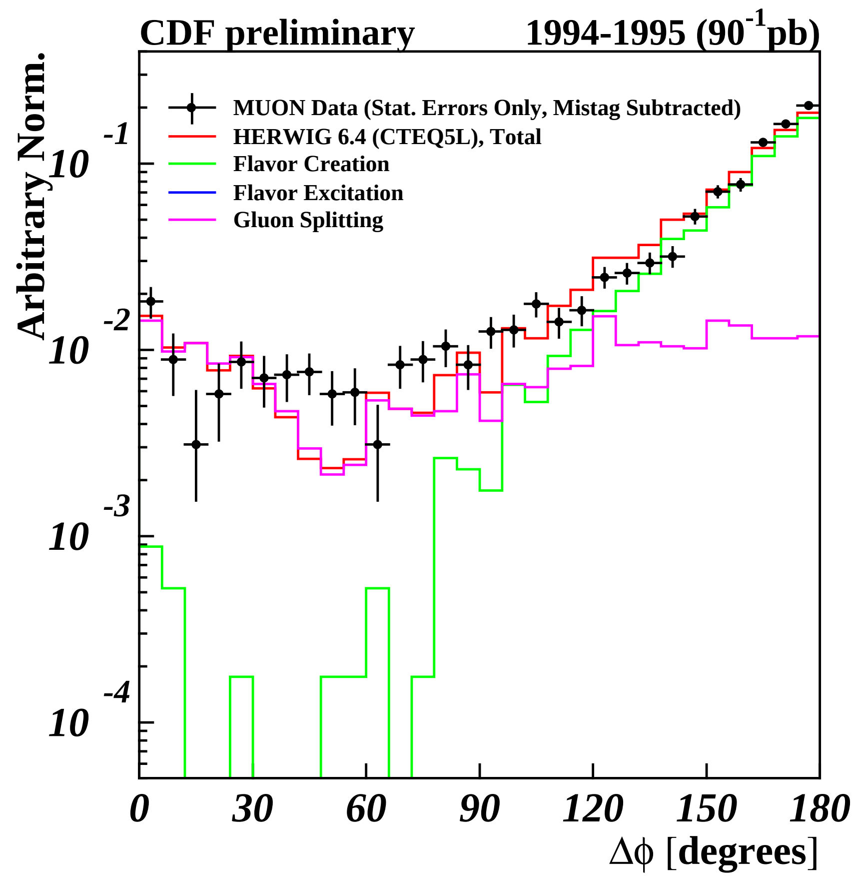


PARP(67) = 1.0 (less ISR)

MC still broader than data near $\Delta\phi = 180°$

Flavor excitation contribution reduced to zero in fit



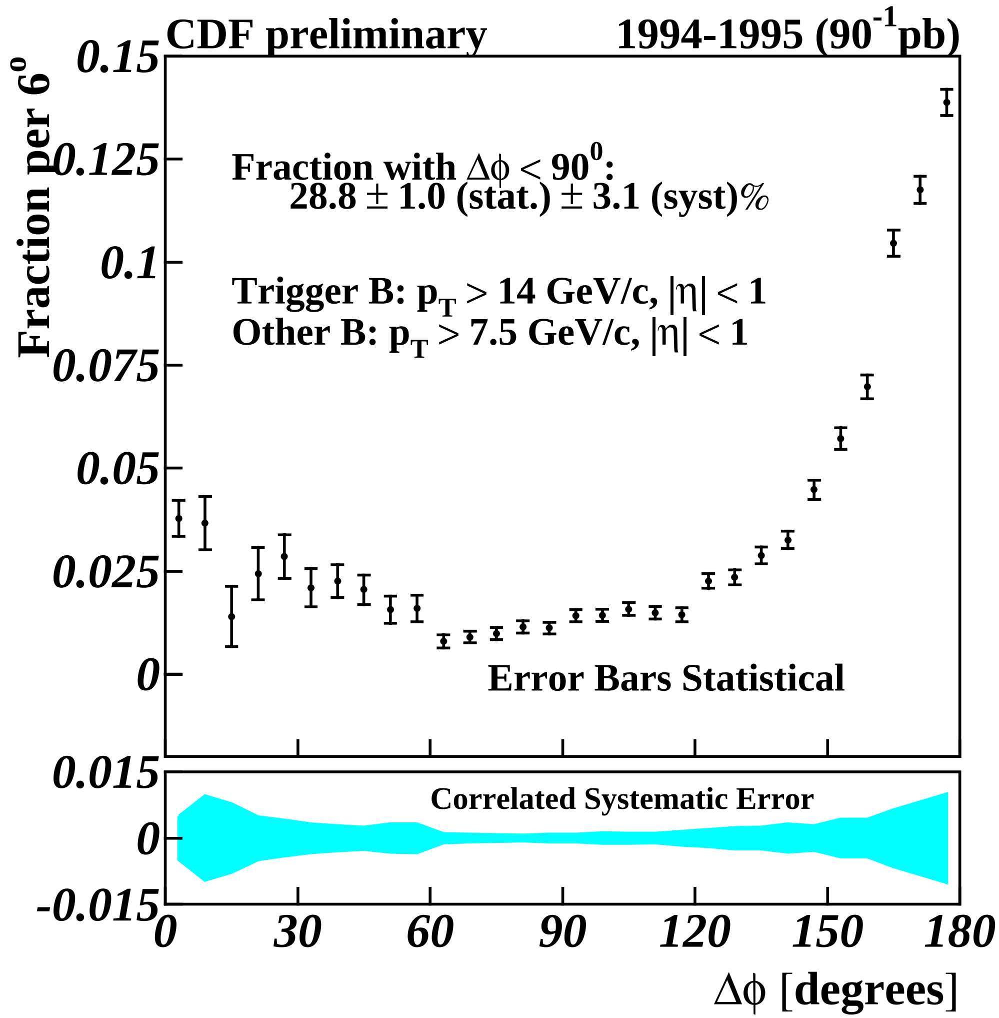


Corrected Data

- Use MC to correct data
  - Relative efficiency
  - Prompt charm
  - Sequential double-tags
- Similar to preliminary results from *J/ψ* + lepton analysis
  - Tag one *B* with *J/ψ*
  - Tag other with lepton
  - Result:

$$\frac{N(\Delta\phi < 90°)}{N(\Delta\phi > 90°)} = 0.52 \pm 0.21$$

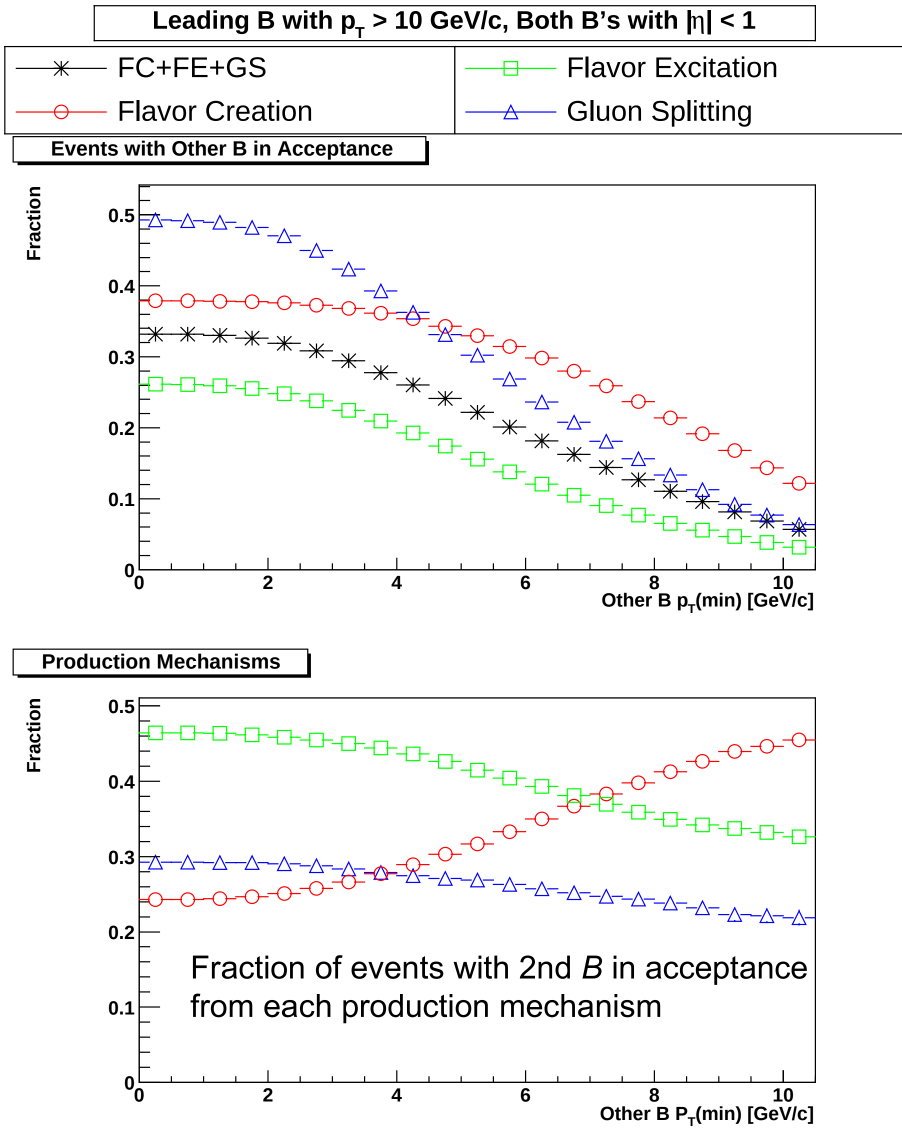
Combined electron and muon data



Important for B Mixing Measurements

- Flavor tagging
  - Same-side: use info from b fragmentation
  - Opposite-side: use info from decay of other b
- Correlations
  - How often are both B hadrons in same jet?
  - Where should one look for the other B hadron?
- Acceptance: Is the other B even in the event?

$$A = \frac{N(\text{more than one in central region})}{N(\text{one in central region})}$$



Pythia with PARP(67) = 4.0

CDF Direct Charm Cross Sections (Run II)

- Measure the cross section for D^0, D^+, D^{*0}, and D_s^+ using fully reconstructed decays
- Possible because of secondary vertex trigger (SVT)
  - Uses information from the silicon vertex detector to trigger on tracks with large impact parameter with respect to primary vertex
  - Provides a large sample of fully reconstructed *D* decays
  - Not possible in Run I!
- Motivation
  - No published direct charm cross section from CDF Run I
  - Is the discrepancy seen in the bottom cross section also seen for charm?

Analysis Overview

- Fully reconstruct and count charm mesons in p_T bins
- Measure direct charm fraction
  - Direct = produced directly by $p\bar{p}$ collision
  - Secondary = from *B* decays
- Determine trigger and reconstruction efficiencies
- Determine Luminosity
- Calculate cross section

$$\sigma_i = \frac{\frac{1}{2} N_i \cdot f_{D,i}}{L \cdot \varepsilon_i \cdot Br}$$

Number reconstructed

Average of D and $\bar{D}$

Direct fraction

Measured cross section in p_T bin i

Branching fraction to reconstructed final state (from PDG)

Luminosity

Trigger and reconstruction efficiency

Signal Reconstruction

Large, clean signals with small statistical and systematic uncertainties

Data: 5.8 pb^{-1} from Feb-Mar 2002 (only a small fraction of data now available!)

$$D^0 \to K^-\pi^+$$

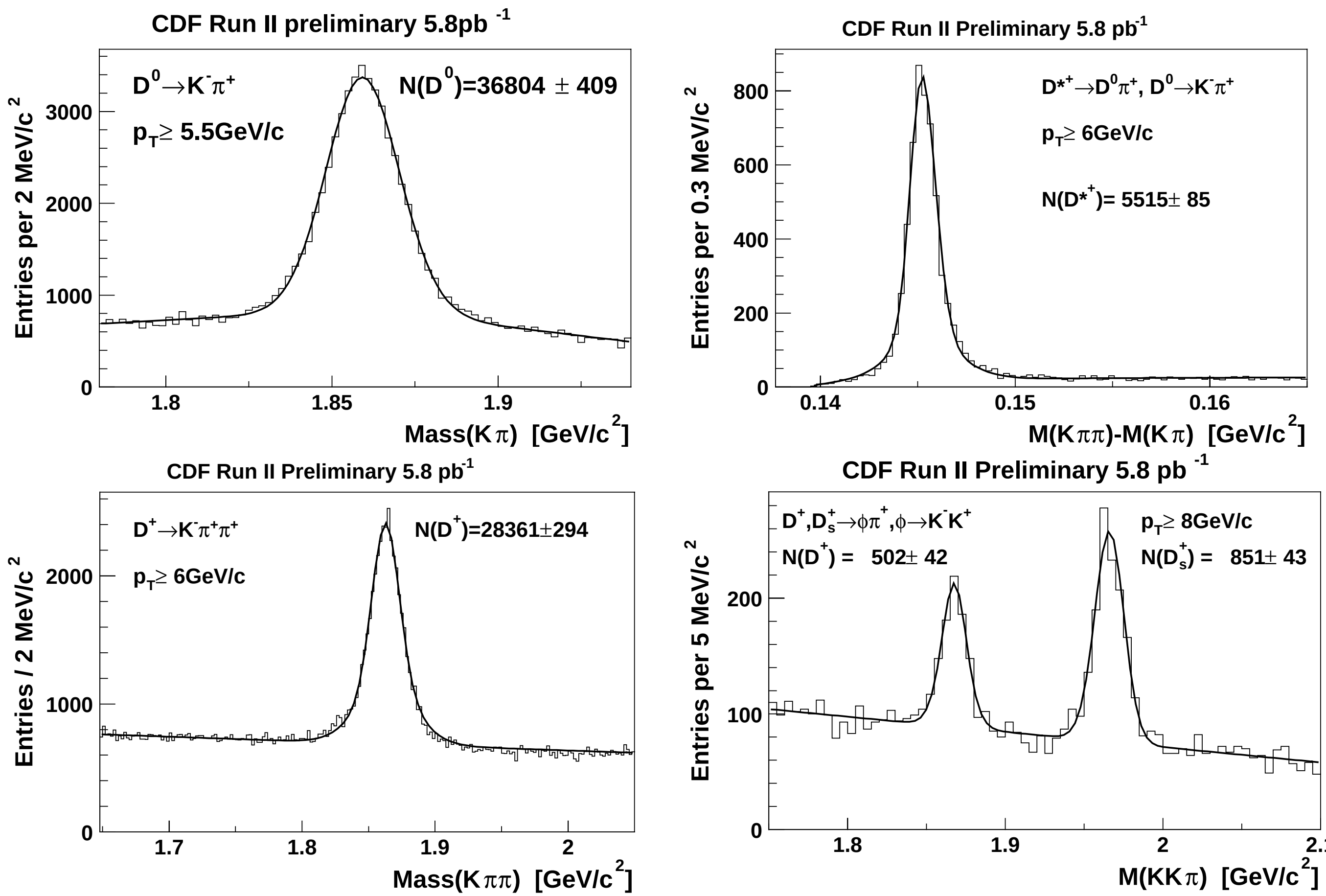
$$D^{*+} \to D^0\pi^+$$

$$D^0 \to K^-\pi^+$$

$$D^+ \to K^-\pi^+\pi^+$$

$$D_s^+ \to \phi\pi^+$$

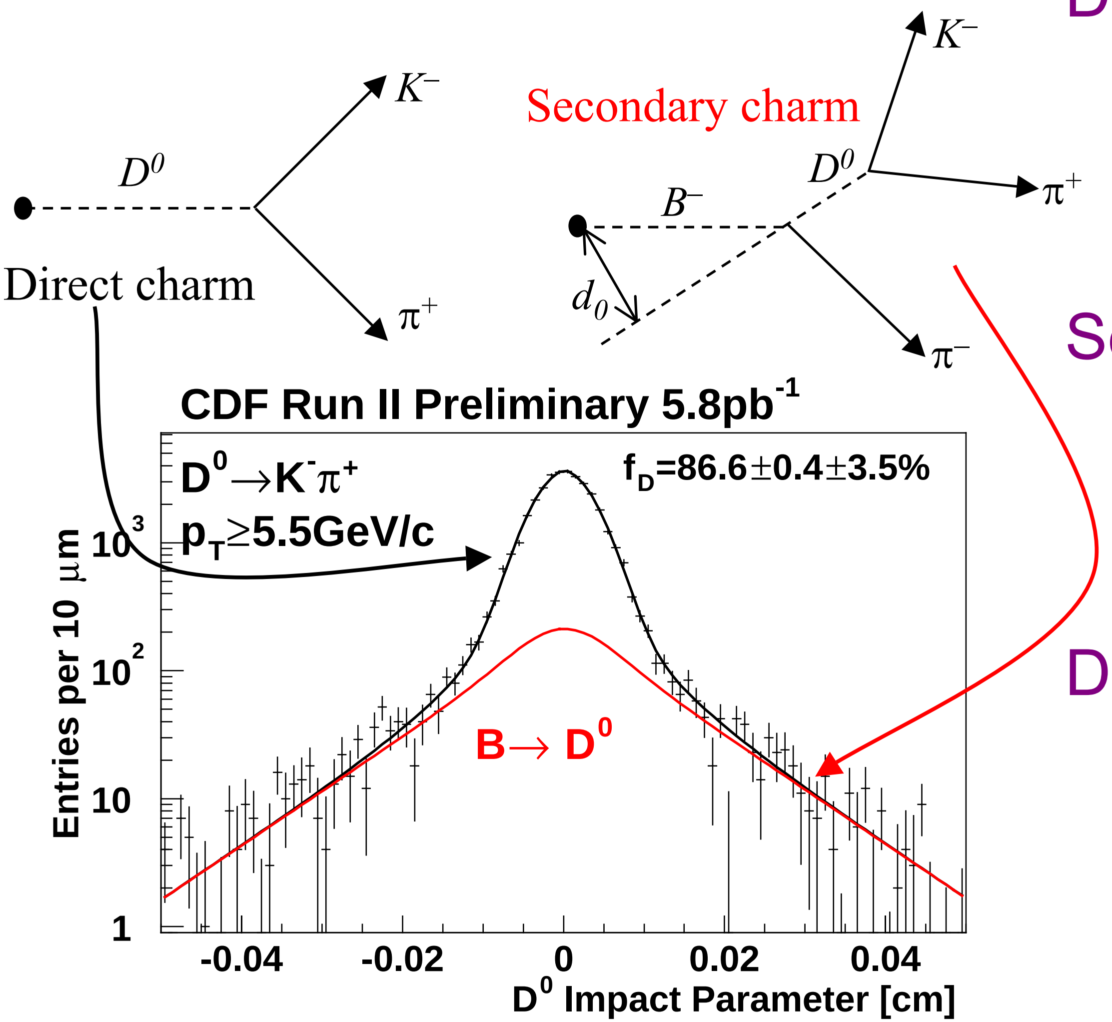
$$\phi \to K^-K^+$$



Minimum p_T, L_{xy} cuts imposed, No PID used

Separating Direct and Secondary Charm

Fraction determined by fitting impact parameter distribution



Direct Charm

- Points at I.P. within resolution
- Distribution determined from K_s^0 decays

Secondary Charm

- Broader d_0 distribution
- Distribution determined from MC convoluted with d_0 resolution

Direct Charm Fractions

- D^0: 86.5±0.4 ±3.5%
- D^{*+}: 88.1±1.1 ±3.9%
- D^+: 89.1±0.4 ±2.8%
- D_s^+: 77.3±4.0 ±3.5%

Trigger and Reconstruction Efficiency

- Use data to measure single track efficiencies
  - XFT and SVT (trigger)
  - SVX and COT (tracking)
  - Dependence on correlations between two trigger tracks
- Use single-track efficiencies to create parameterized detector simulation
- Calculate ε for each p_T bin using NLO MC and parameterized detector simulation
  - Reweight MC so D p_T distribution matches data
  - Include Dalitz structure for $D^+ \rightarrow K^- \pi^+ \pi^+$

Integrated Cross Sections

- For all cross sections, $|y(D)| \leq 1$
- Summed over all p_T bins, we get
  - $\sigma(D^0, p_T \geq 5.5$ GeV/c$) = 13.3 \pm 0.2 \pm 1.5$ μb
  - $\sigma(D^{*+}, p_T \geq 6.0$ GeV/c$) = 5.2 \pm 0.1 \pm 0.8$ μb
  - $\sigma(D^+, p_T \geq 6.0$ GeV/c$) = 4.3 \pm 0.1 \pm 0.7$ μb
  - $\sigma(D_s^+, p_T \geq 8.0$ GeV/c$) = 0.75 \pm 0.05 \pm 0.22$ μb

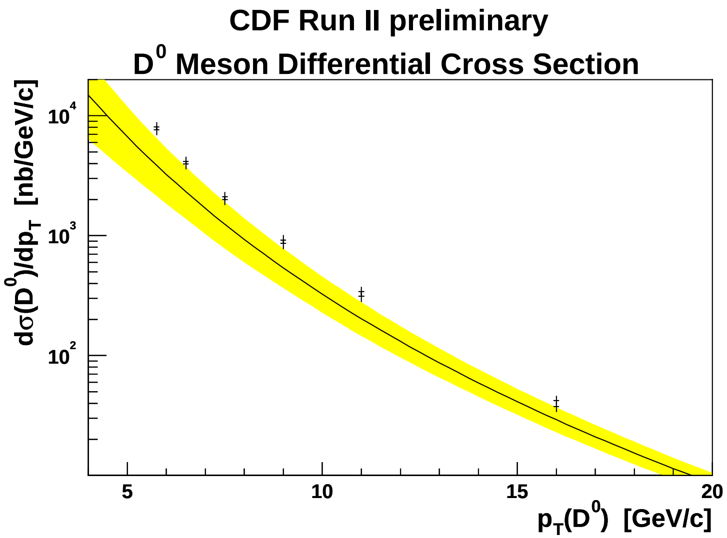
$$\sigma_i = \frac{\frac{1}{2} N_i \cdot f_{D,i}}{L \cdot \varepsilon_i \cdot Br}$$

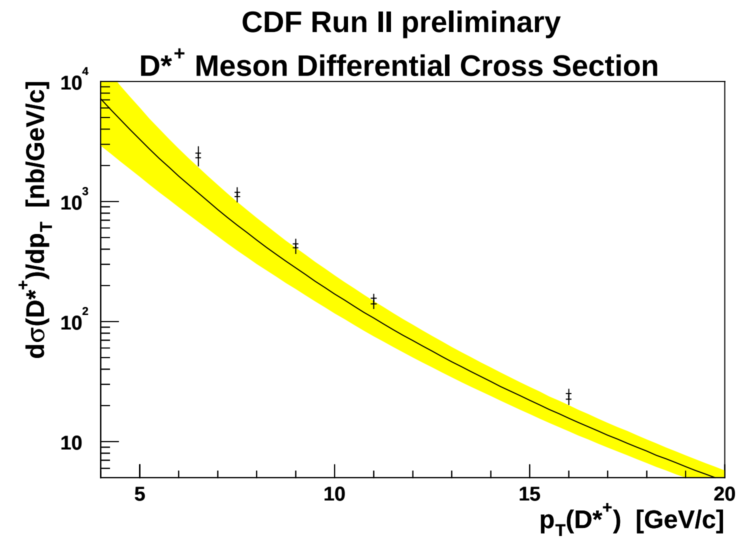
PDG 2002 Branching Ratios

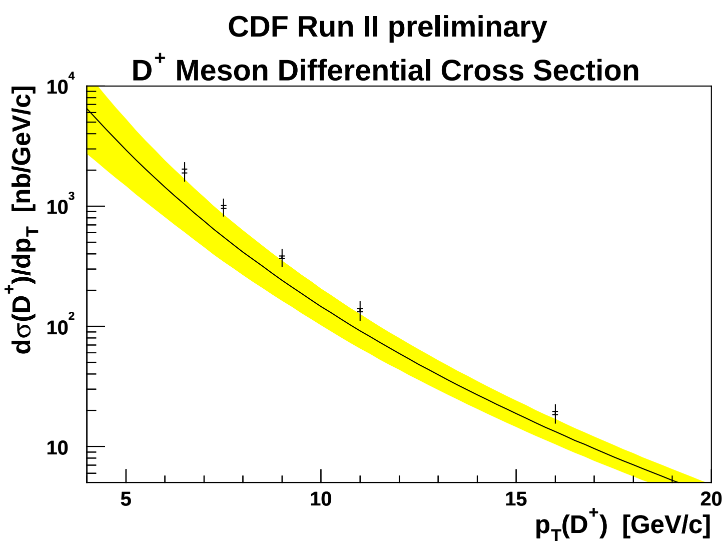
$D^0 \to K^- \pi^+$	$3.80 \pm 0.09\%$
$D^0 \to K^+ \pi^-$	$(1.48 \pm 0.21) \times 10^{-4}$
$D^{*+} \to D^0 \pi^+$	$67.7 \pm 0.5\%$
$D^+ \to K^- \pi^+$	$9.1 \pm 0.6\%$
$D_s^+ \to \phi \pi^+$	$3.6 \pm 0.9\%$
$\phi \to K^+ K^-$	$49.2 \pm 0.7\%$

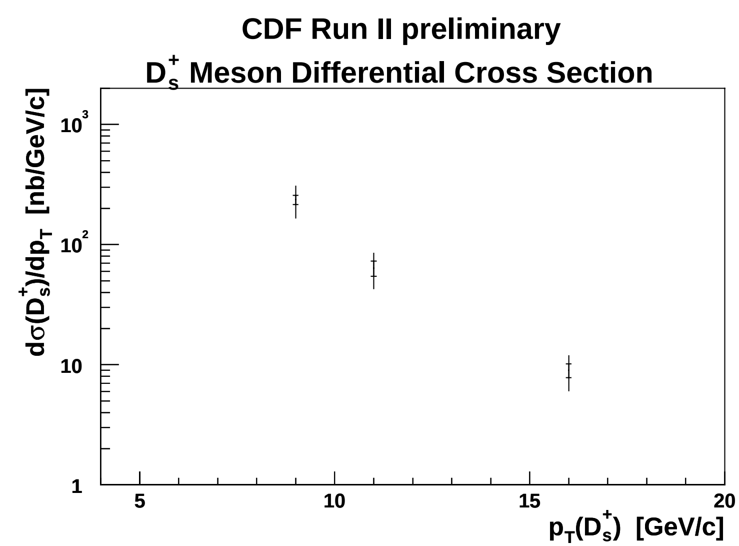
Differential Cross Section Results

Theory curve from M. Cacciari and P. Nason: Resummed perturbative QCD (FONLL)

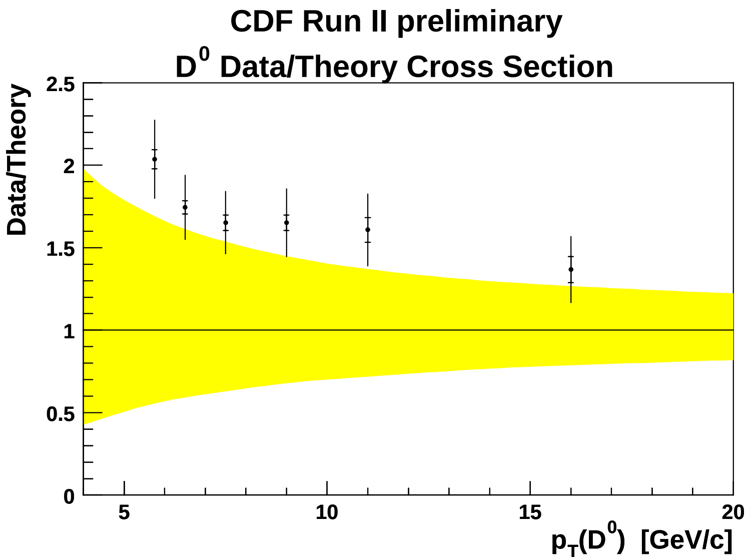


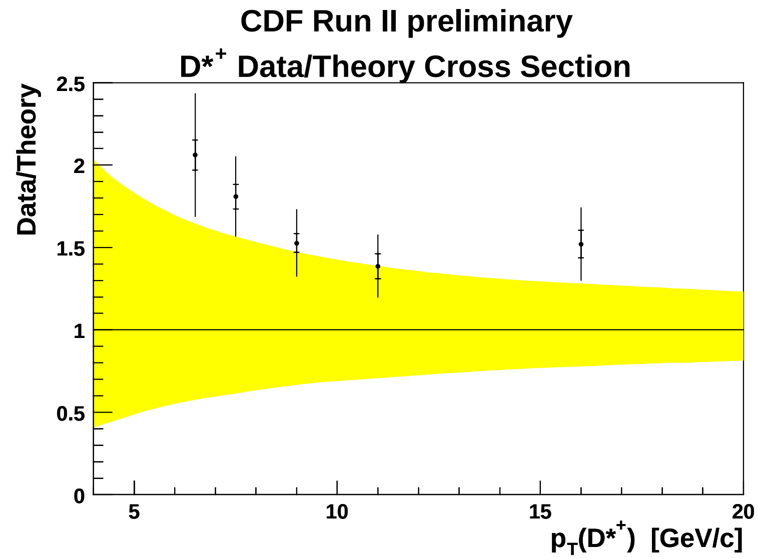


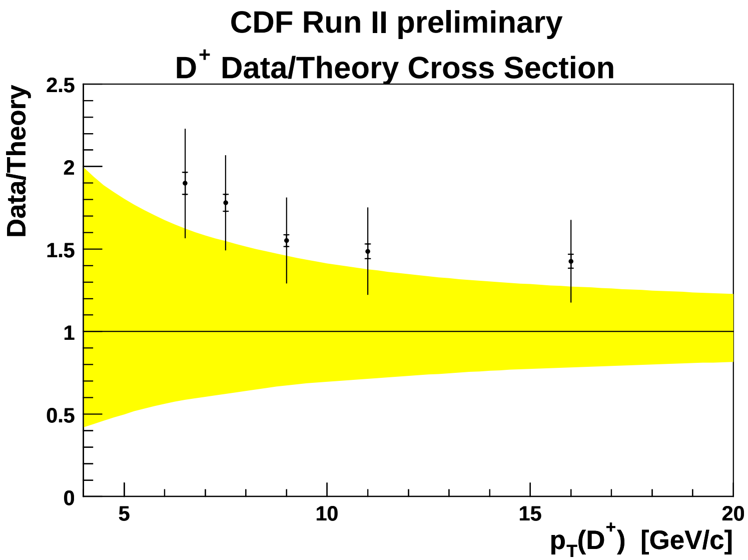




Ratio of Data to Theory







- Data higher than theory, but not inconsistent with uncertainties
- Data and theory have similar shape

DØ *b*-jet Cross Section (Run II)

- Use muon-tagged calorimeter jets to calculate the *b*-jet cross section
  - *b*-jet = hadronic jets carrying *b* flavor
  - *b* flavor detected through semileptonic *B* decays to muons
  - Jet detected by energy deposited in $\Delta R = 0.5$ cone
- Motivation
  - Complementary to *b* quark and *B* hadron cross section measurement
  - Jets are observable while quarks are not
  - Not as sensitive to fragmentation and decay models as quark or hadron measurements

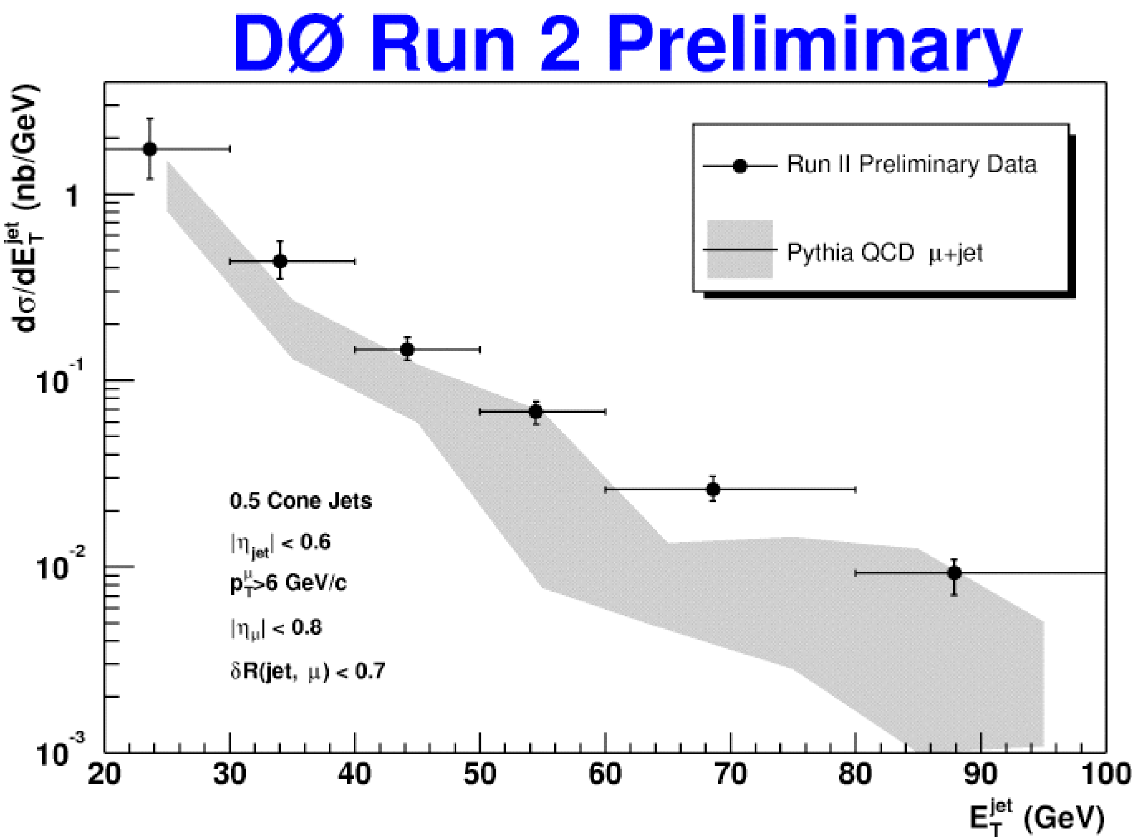
Similar analysis published in Run I

Analysis Overview

- Select jets containing muons
  - Use 3.4 pb-1 of Run II data (1.96 TeV, 02/28/02-05/10/02)
  - Data selection and kinematic cuts:
    - Jet cone of ΔR = 0.5
    - $|\eta^{jet}| < 0.6$
    - $E_T^{jet} > 20$ GeV
    - $|\eta^{\mu}| < 0.8$
    - $p_T^{\mu} > 6$ GeV/c
    - $\Delta R(\text{jet},\mu) < 0.7$
- Measure μ + jet cross section
- Extract *b*-content using p_T^{Rel}
- Correct for jet energy resolution and *b*-jet acceptance

μ + jet Cross Section

b-jet fraction not unfolded



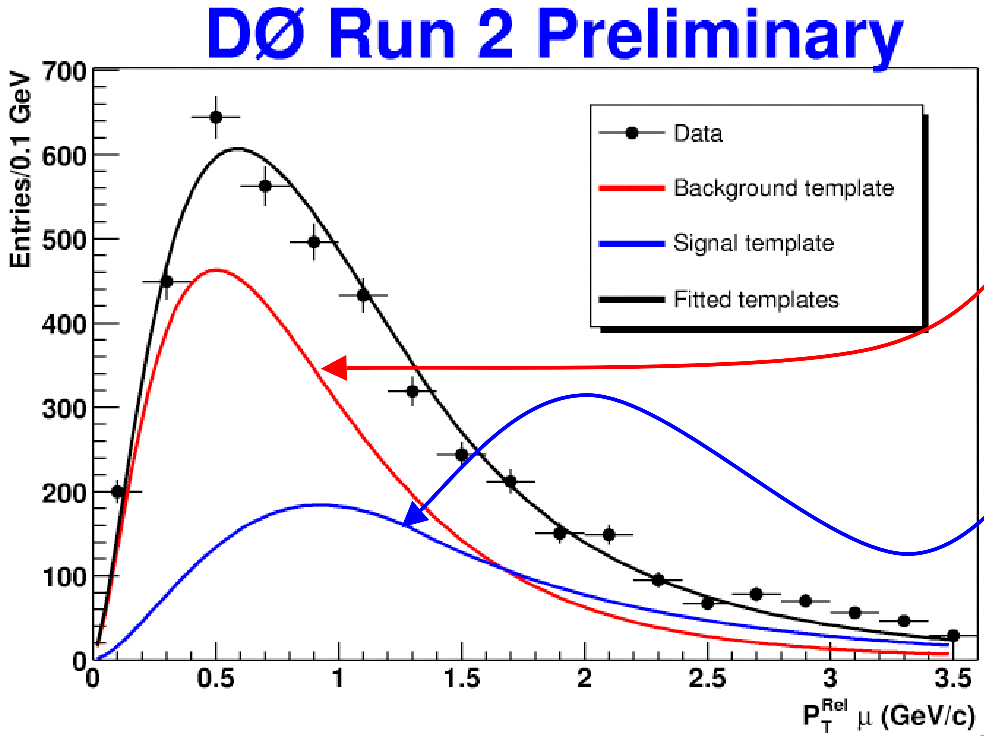
Number of μ-jets counted per E_T bin

$$\frac{d\sigma(\mu - jet)}{dE_T^{jet}} = \frac{1}{\varepsilon(\mu, jet)\int Ldt}\frac{dN}{dE_T^{jet}}$$

Muon and jet trigger and reconstruction efficiencies

Luminosity

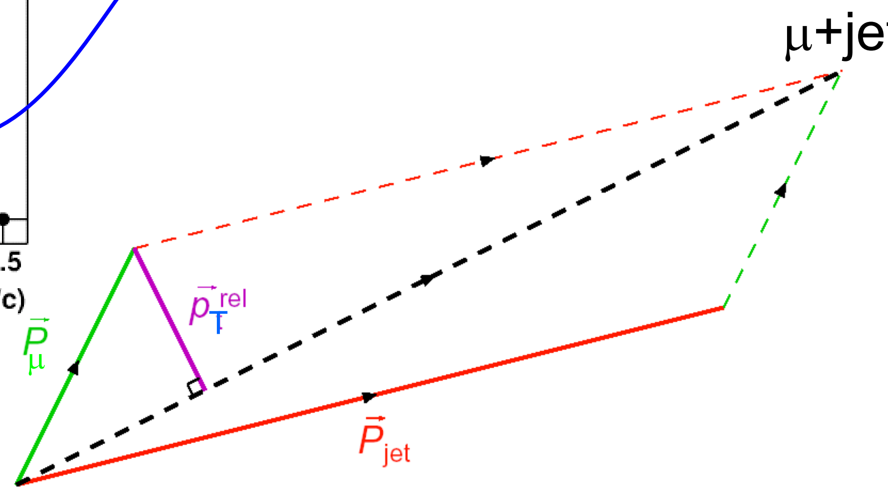
Fit the p_T^{rel} distribution in each E_T bin to extract the b-jet component



Background template = p_T^{rel} from generic QCD data

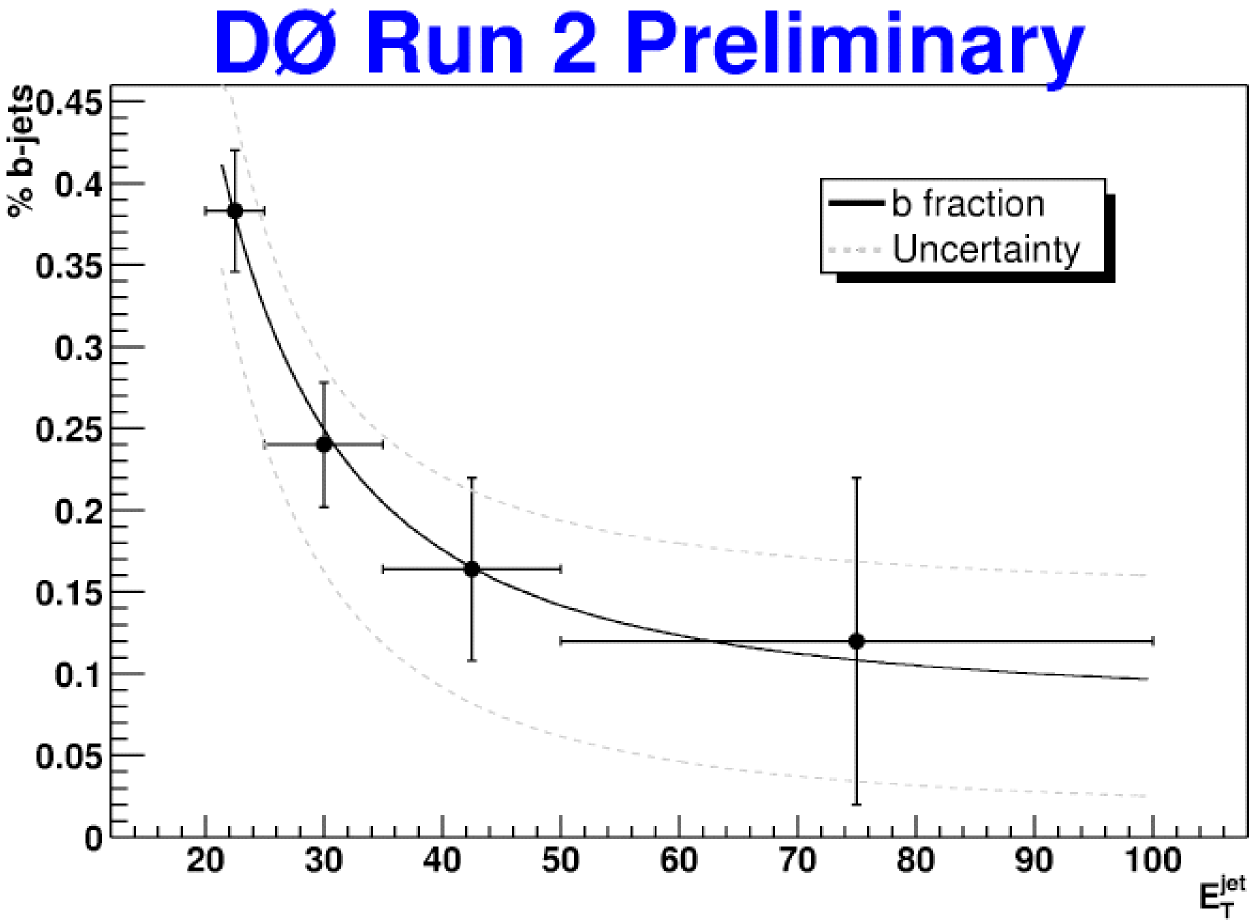
Signal template = b p_T^{rel} from MC

p_T^{rel} in the first E_T bin (20-25 GeV)



p_T^{rel} = component of μ momentum perpendicular to μ-jet direction

b-jet Fraction as a function of jet E_T



# of bins constrained by statistical limitations of background templates

fitted with functional form: $a + b/E_T^{jet}$

b-jet Cross Section Results

Average over b and $\bar{b}$

μ-jet cross section, accounting for b fraction and E_T unsmearing

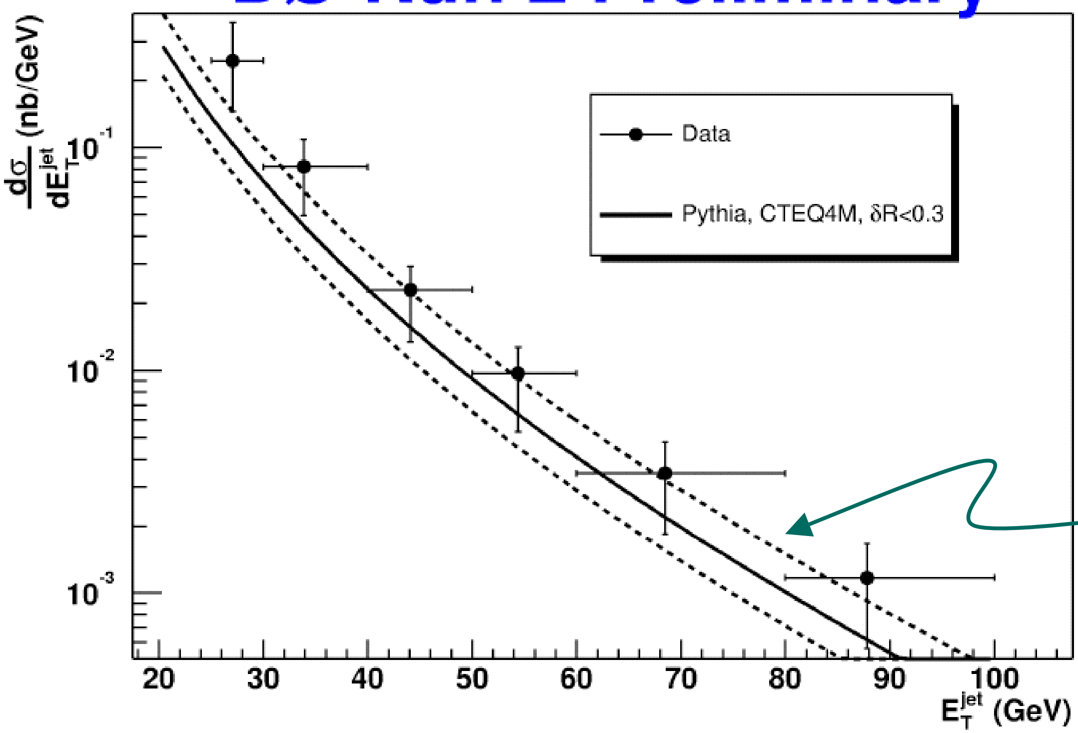
Final corrected b-jet Cross Section

$$\frac{d\sigma(b-jet)}{dE_T^{jet}} = \frac{1}{2}\frac{1}{BR(b\rightarrow\mu)\cdot A(E_T)}\frac{d\sigma_b(\mu-jet)}{dE_T^{jet}}$$

Branching ratio from PDG

Muon tagging acceptance

DØ Run 2 Preliminary



Dominant experimental error from jet energy scale

band covers uncertainty due to:

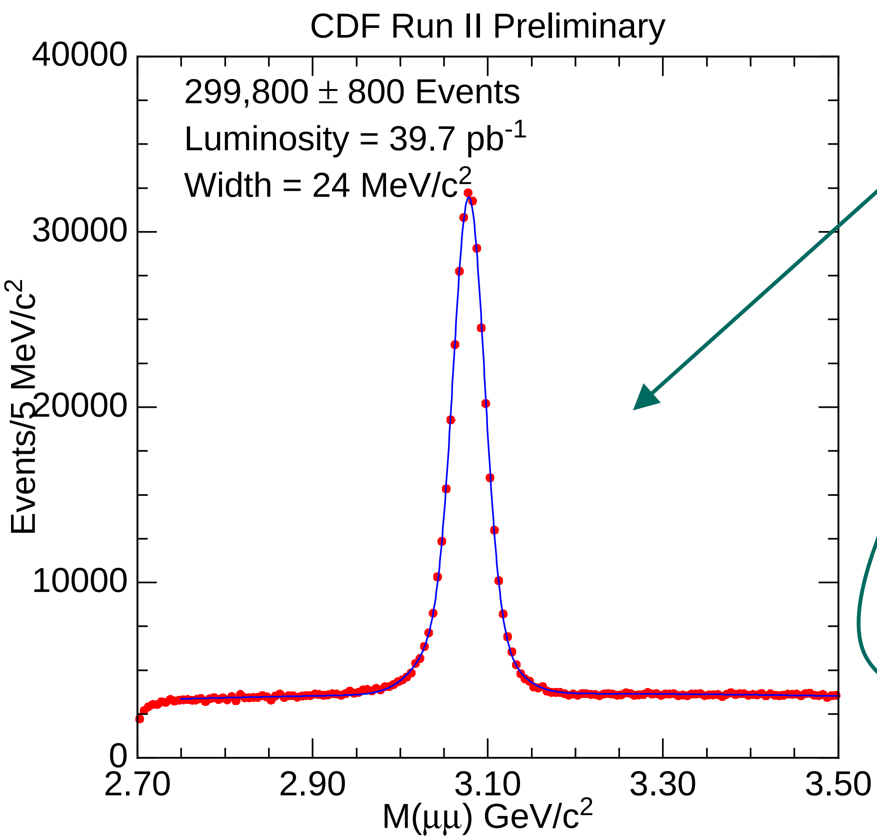
- b-quark mass
- Renormalization/factorization scales
- PDF's
- Fragmentation functions

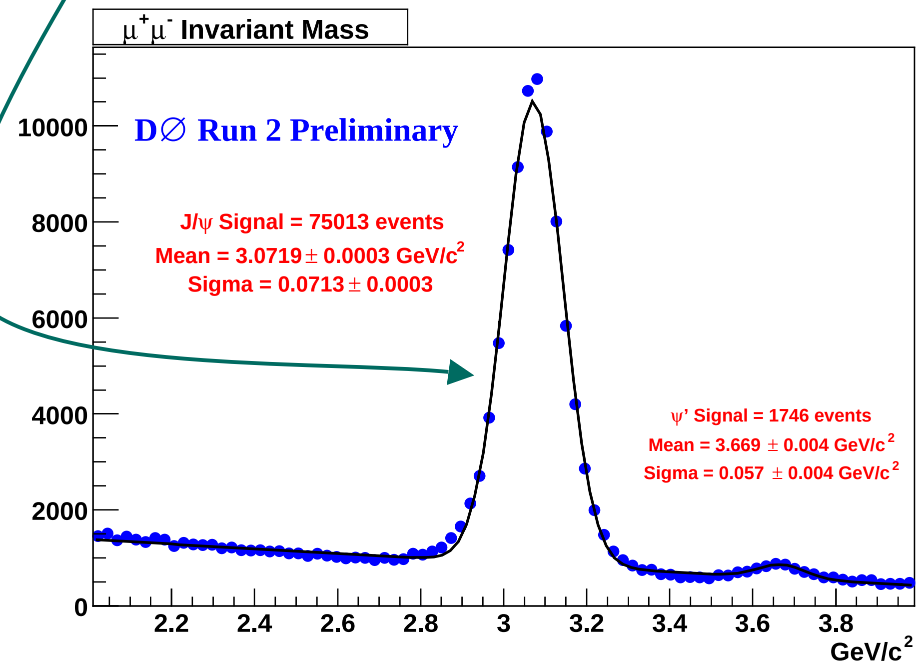
DØ and CDF J/ψ Production (Run II)

- Main production mechanisms at Tevatron
  - Direct QCD production $c\bar{c}$ bound states (described by non-relativistic QCD models)
  - Secondary decays from *B* hadron production
- $J/\psi \rightarrow \mu\mu$ (BR $\approx$ 6%) is easy to trigger on
- Motivation for measuring J/ψ production:
  - Probe regions not measured in Run I
    - Low p_T
    - Intermediate pseudo-rapidity, $0.6 < |\eta| < 2.0$
  - Further investigations of *b* quark and *B* hadron production cross sections

Large, Clean Data Samples

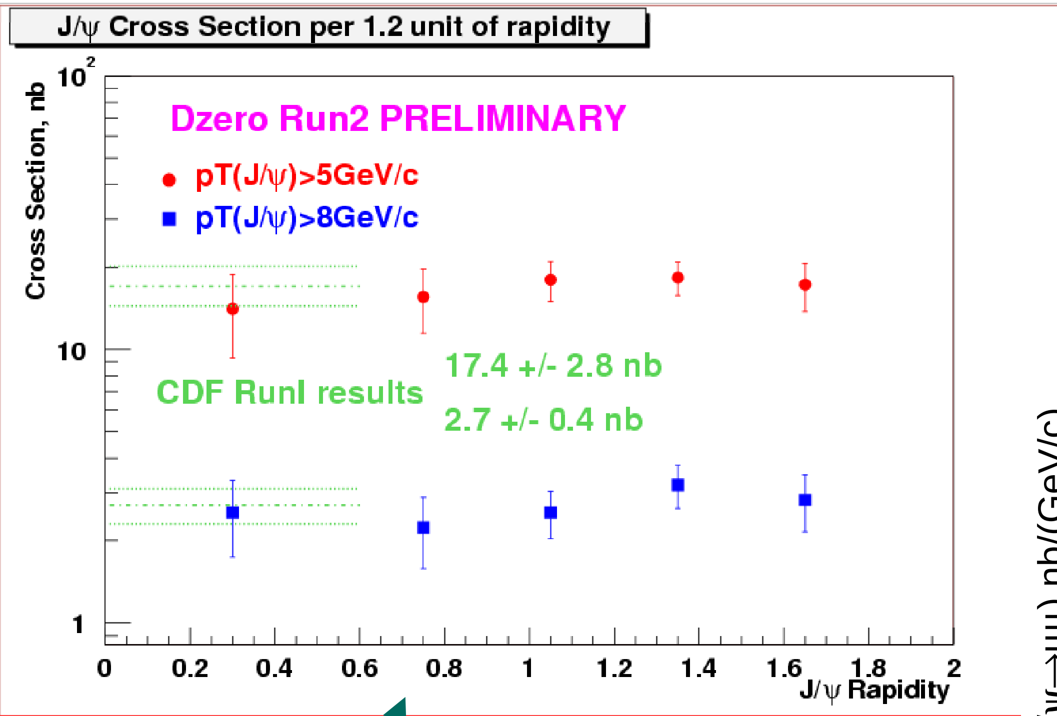
- CDF data from February to October 2002 (39.7 pb^{-1})
- DØ data from February to May 2002 (4.7 pb^{-1}) (larger, more recent sample shown below)





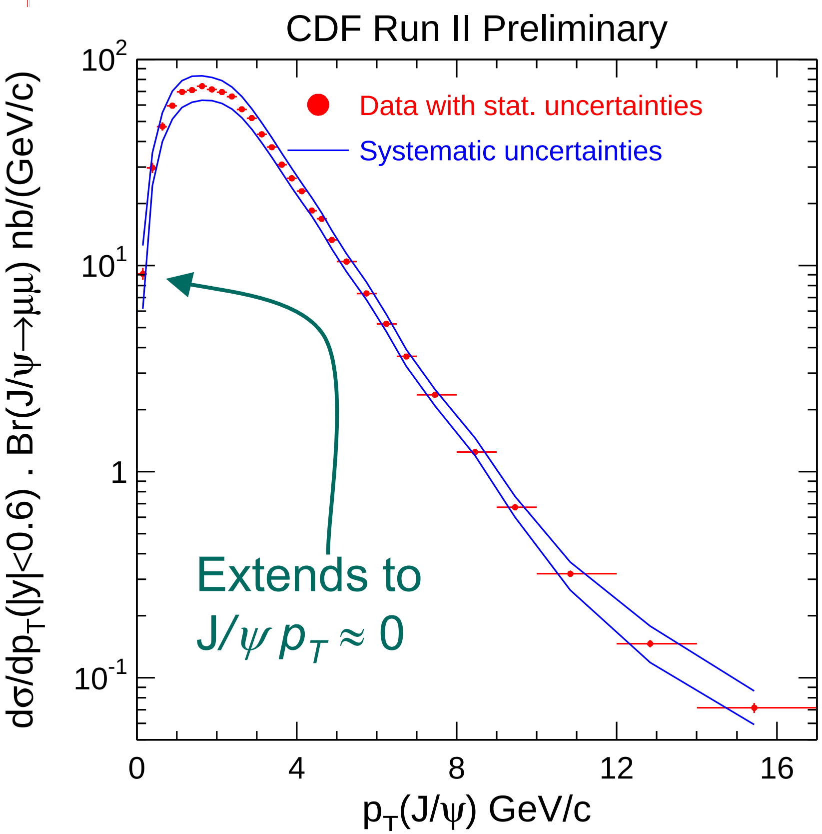
~ 17% from secondary decays based on lifetime fits

Inclusive Cross Sections Measured



Binned by J/ψ rapidity

Includes both direct and secondary decays



Extends to $J/\psi\ p_T \approx 0$

Unfolding of direct and secondary contributions in progress

Summary

- *B* Hadron Correlations
  - Higher order production mechanisms important at Tevatron
  - Flavor excitation and gluon splitting needed in PYTHIA and HERWIG to model data
- Heavy Flavor Cross Sections
  - Direct charm cross sections measured at CDF
  - Bottom-jet cross sections measured at DØ
  - Expect more to come!
- J/ψ Production
  - Inclusive cross section measured
  - Unfolding of contributions from direct and secondary production in progress